THE REMNANT AND ORIGIN OF THE HISTORICAL SUPERNOVA 1181 AD

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Andreas Ritter
Department of Physics
The University of Hong Kong,
Chong Yuet Ming Physics Building
Pokfulam Road, Hong Kong
aritter@hku.hk

Quentin A. Parker*
Department of Physics
The University of Hong Kong,
Chong Yuet Ming Physics Building
Pokfulam Road, Hong Kong
quentinp@hku.hk

Foteini Lykou
Konkoly Observatory
Research Centre for Astronomy
and Earth Sciences
Konkoly-Thege Miklós út 15-17
1121 Budapest, Hungary
foteini.lykou@csfk.org

Albert A. Zijlstra
Jodrell Bank Centre for Astrophysics
The University of Manchester
Oxford Road, M13 9PL
Manchester, UK
albert.zijlstra@manchester.ac.uk

Martín A. Guerrero
Instituto de Astrofísica
de Andalucía (IAA-CSIC)
Glorieta de la Astronomía S/N
18008 Granada, Spain
mar@iaa.es

Pascal Le Dû
Kermerrien Observatory
F-29840 Porspoder, France
pascal.le.du@shom.fr

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ABSTRACT

The guest star of AD 1181 is the only historical supernova of the last millennium that is without a definite counterpart. The previously proposed association with supernova remnant G130.7+3.1 (3C58) is in strong doubt because of the inferred age of this remnant. Here we report a new identification of SN 1181 with our co-discovery of the hottest known Wolf-Rayet star of the Oxygen sequence (dubbed

*Corresponding author

"Parker's star") and its surrounding nebula Pa 30. Our spectroscopy of the nebula shows a fast shock with extreme velocities of ≈1,100 km s^{-1}. The derived expansion age of the nebula implies an explosive event ≈1,000 years ago which agrees with the 1181 event. The on-sky location also fits the historical Chinese and Japanese reports of SN 1181 to 3.5 degrees. Pa 30 and Parker's star have previously been proposed to be the result of a double-degenerate merger, leading to a rare Type Iax supernova. The likely historical magnitude and the distance suggest the event was subluminous for normal supernova. This agrees with the proposed Type Iax association which would also be the first of its kind in the Galaxy. Taken together, the age, location, event magnitude and duration elevate Pa 30 to prime position as the counterpart of SN 1181. This source is the only Type Iax supernova where detailed studies of the remnant star and nebula are possible. It provides strong observational support for the double-degenerate merger scenario for Type Iax supernovae.

Keywords (stars:) supernovae: general · (stars:) supernovae: individual: historical · stars: Wolf–Rayet · ISM: supernova remnants

1 Introduction

Only 9 historically recorded supernova (SN) explosions are known in the Galaxy [Green, 2002]. In only 5 cases has the remnant of the supernova been identified. For the other cases, the remnant is not known with certainty. The remnant is crucial for identifying the type of supernova, whilst the known time of the explosion and duration constrain the models of the evolution of the remnant.

Here, we consider the historical 'Guest Star' of 1181 AD recorded by Chinese and Japanese astronomers [Hoffmann et al., 2020]; it remained visible for 185 days from Aug 6, 1181 to Feb 6, 1182 AD [Hsi, 1957]. The supernova remnant (SNR) or pulsar wind nebula G130.7+3.1 (3C58, which we will hereafter use to refer to this SNR) are located in its vicinity [Stephenson and Green, 1999, Green, 2002] and have till now been considered as linked with SN 1181. However, a precise estimate of the expansion age of this nebula of 7,000 years, based on NVSS radio observations over 20 years, and the spin-down age of the pulsar (5,400 years) by Bietenholz [2006] have put the association in serious doubt, although not completely excluding it [Kothes, 2013]. A strong argument for this association was that until now there was no other candidate known for the remnant. This left SN 1181 as the youngest Galactic supernova without a firmly confirmed remnant. We propose that the recently discovered nebula Pa 30 and its extreme central star [Gvaramadze et al., 2019] are in fact the remnant and residual core of the 1181 AD explosion.

The nebula Pa 30 was discovered on 25th August 2013 from the Wide-field Infrared Survey Explorer (*WISE*) mid-IR image archive [Cutri and et al., 2012] by Dana Patchick [Kronberger et al., 2016] from our affiliated 'Deep Sky Hunters' (DSH) amateur astronomer group, and is included in the HASH PN database[2] [Parker et al., 2016] as Pa 30. The *WISE* W3 ($11\mu m$) band shows a round nebula, whereas the dominant shape in the W4 ($22\mu m$) band is donut-like inside a much fainter halo. Narrow-band [O III] imaging observations obtained by the DSH group on the 2.1m KPNO telescope in September 2013 indicate a very faint, diffuse, circular emission feature. The nebula is a strong source of diffuse X-ray emission [Oskinova et al., 2020]. Multi-wavelength images of the nebula are shown in Figure 1. The bright central star (CS) is both hydrogen-poor and helium-poor, and has a unique emission-line spectrum as shown by Gvaramadze et al. [2019] and from our independent spectroscopy.

On careful scrutiny both sets of our observations (see below) revealed two faint optical emission lines species in the nebula: the [S II] 6716 and 6731Å doublet, and the [Ar III] 7136Å line. The [S II] in particular shows extreme velocity splitting with an expansion velocity up to $v_{\rm exp} \approx 1{,}100 \pm 100$ km s^{-1} (Fig. 2). The velocity is constant up to $50''$ from the CS, followed by a sharp decline to systemic velocity at ≈$100''$. We also extracted the star's spectrum after it was first brought to our attention by Pascal Le Dû, an amateur collaborator of the corresponding author, where its extreme nature became clear [e.g. see Gvaramadze et al., 2019] and it was thereafter dubbed "Parker's" star.

Taking the latest *Gaia* distance of 2.30 ± 0.14 kpc [Bailer-Jones et al., 2021], the highest velocity extends to a total diameter of 2.2 ± 0.4 pc, and the slower emission extends to about twice that diameter. If we assume that the 1,100 km s^{-1} gas is expanding at a constant velocity, and that the uncertainty on the expansion velocity is 10%, the highest velocity shell has a kinematic age of 990^{+280}_{-220} years.

Oskinova et al. [2020] estimated an age for the shell based on the Sedov solution scaling relation [see Borkowski et al., 2001, Oskinova, 2005] for supernova remnants of ∼1,000 years, in excellent agreement with the measured kinematic age of the shell. This agreement supports the identification of the nebula as an SNR.

[2] `http://hashpn.space`

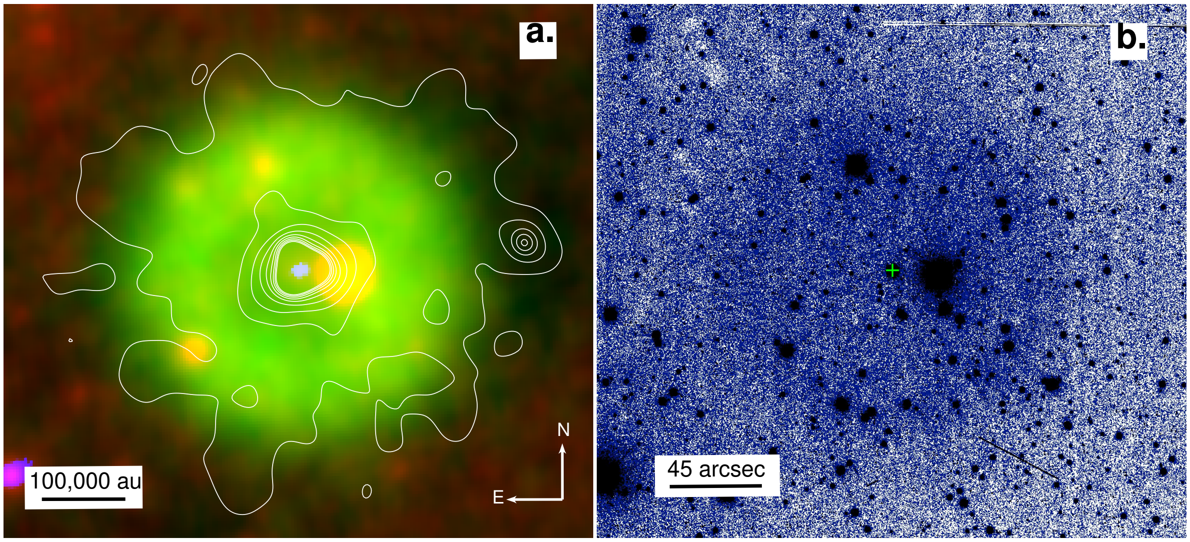


Figure 1: **(a.)** False colour image of Pa 30 where *red* stands for *WISE* 11 micron, *green* for *WISE* 22 micron, and *blue* for *GALEX* near-UV, with *XMM-Newton* contours (10 levels, linear scale). Only the CS is visible in the near-UV and the majority of the X-ray emission originates from the core of the nebula. A background point source is seen westward of the CS in the *XMM-Newton* contour map. **(b.)** 2.1-m KPNO [O III] image, which we have stacked and rebinned from individual frames to enhance the low surface brightness, diffuse shell. The green cross in the center of the image marks the location of the CS. Panels (a) and (b) are reproduced at the same angular scale. At the *Gaia* distance of Pa 30 of 2.30 ± 0.14 kpc, an angular scale of $45''$ translates to about 100,000 AU.

The kinematic age agrees well with SN 1181 recorded 840 years ago and provides a strong temporal argument for association. The second argument for the association comes from the position concordance. Of the recorded 'guest stars' listed in Hoffmann et al. [2020], SN 1181 is the only one that matches the estimated explosion date and the location of Pa 30 to within the errors. Averaging the five reported positions for this historical SN (Hoffmann et al.) and transforming the average to J2000, the separation on the sky between the recorded position and the position of Parker's star is only 3.5 degrees (see Table 1), well within the uncertainties. The *Gaia* proper motion for the star of 2.7 milliarcsec yr^{-1} would only shift it by $\sim$3 arcseconds in the intervening period. The only other viable alternative [and indeed the previously favoured association, Kothes, 2013] is SNR 3C58 at $\sim$4.5 degrees away from the SN 1181 position.

Figure 3 shows the best estimated general location of SN 1181. The two candidates Pa 30 and 3C58 are indicated, as is the best estimate for the location of SN 1181 with a 5 degree radius error circle. The SN was reported to have occurred near Wangliang in Huagai, invading Chuanshe [Hsi, 1957, spelling adopted from Hoffmann et al.]. These Chinese asterisms are shown by the three red-lined constellations, as taken from Hoffmann et al. The location of Chuanshe is not known with full certainty: the dashed line shows the location according to Stephenson and Green [2002]. The text suggests that SN 1181 should be between the two constellations. Pa 30 fits this well. The 3C58 alternative is located in or south of Chuanshe, not obviously associated with Huagai. We also note that the location of 3C58 would have been more easily described as close to the bright (3rd magnitude) star ε Cas.

The magnitude of SN 1181 is not known with certainty but it was compared in the manuscripts to Saturn. With the reasonable assumption that this refers to its brightness, then the magnitude at peak may have been around $m_V \sim -0.5$ to $+1.0$. This agrees with the fact it was obvious enough to be picked up in China and Japan who at the time had well developed astronomical capacity, but was missed in others (e.g. Korea and Europe). For a distance of 2,300 pc and an extinction $A_V = 2.4$ (see Methods), the absolute magnitude becomes $M_V \sim -14$ to -12.5. This is significantly sub-luminous for a typical supernova but is within the range for Type Iax events (see below). The object also remained visible for 185 days. Given that the limit of naked eye visibility is $m \approx 5.5$, this indicates 4.5 – 6 magnitudes of fading over this period. The long period of naked eye visibility is typical for a supernova but does not fit a typical nova duration of days to a few weeks.

Pa 30 is a source of diffuse X-ray emission with a spatial extent in serendipitous *Swift* XRT and pointed *XMM-Newton* EPIC observations larger than that in the mid-IR *WISE* and optical [O III] images (Fig. 1). The *XMM-Newton* EPIC X-ray spectra of both the CS and nebula have been fitted with plasma emission models with significant enrichment in

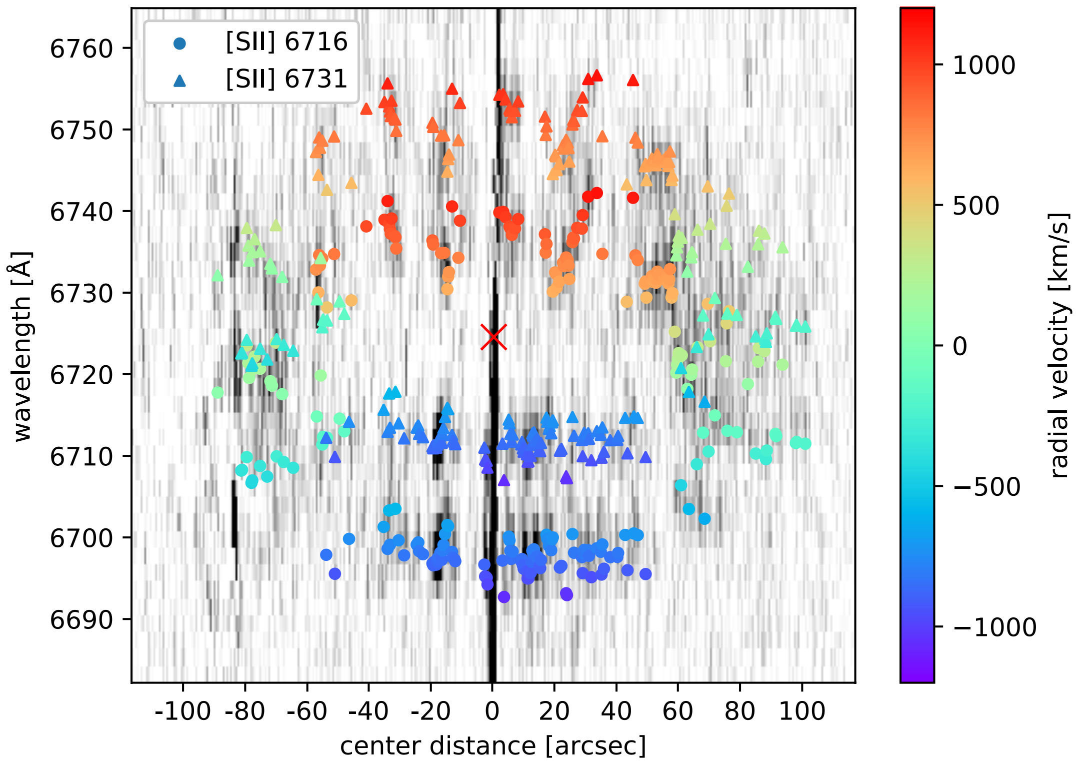


Figure 2: GTC/OSIRIS position-velocity diagram of the [S II] lines (circles: 6716Å, triangles: 6731Å; grey scale in arbitrary data units) along the slit, overplotted with the measured line positions, and color-coded to the radial velocity for each measured line. Left is NNE of the CS, right is SSW. The position of the CS is marked with a red 'X'. Spectral features have been enhanced by subtracting the mean of each spectrum above and below the [S II] lines. The image shows sharp velocity variations with increasing distance from the CS at $\approx -20''$, $-40''$ and $+25''$ where the [S II] lines are also much brighter than for the rest of the long-slit spectrum, indicating strong shock excitation both for the near as well as the far side of the nebula.

neon, magnesium, silicon, and sulphur [Oskinova et al., 2020], which has been interpreted as the result of the incomplete carbon and oxygen fusion expected in Type Ia SNe.

Pa 30 can accordingly be classified as a supernova remnant [Gvaramadze et al., 2019, Oskinova et al., 2020], but the bright CS, which lacks hydrogen and helium, shows it is not a common type. Instead it points at a Type Iax supernova as suggested by Oskinova et al., that is, a sub-luminous SNe Ia event in which the star does not self-destruct. While the exact mechanisms leading to a Type Iax SN are still not fully understood, they are believed to arise from either the failed detonation of a Carbon-Oxygen (CO) White Dwarf (WD) accreting material from a Helium donor star [single degenerate scenario, e.g. Kromer et al., 2015, Jordan et al., 2012] or from a CO WD merging with a heavier Oxygen-Neon (ONe) WD [double degenerate scenario, Kashyap et al., 2018] where the accretion disk itself deflagrates.

A key discriminant between typical SN of Type Ia and Type Iax is the expansion velocity with $\sim$10,000 km s^{-1} for Type Ia and only 2,000–7,000 km s^{-1} for Type Iax [Jha, 2017]. Our measured expansion velocity for the nebula is 1,100 km s^{-1}, which argues in favour of a Type Iax event. Type Iax show a large range of peak magnitudes, which at the faint end (-13 to -14) [Jha, 2017] overlap with the likely magnitude for SN 1181 at a distance of 2,300 pc. This also independently supports this classification.

Based on the current stellar luminosity, Pa 30 is likely a double degenerate merger (Gvaramadze et al.) where Oskinova et al. interpret it as a ONe-CO WD merger based on the nebula's neon abundance. Models for high-mass ONe-CO mergers [Kashyap et al., 2018] predict a faint SN Iax with an absolute magnitude of only -11.3 mag. This is a bit fainter than what we find for SN 1181 but indicates that the Oskinova et al. interpretation may be supported by the faint magnitude of the event.

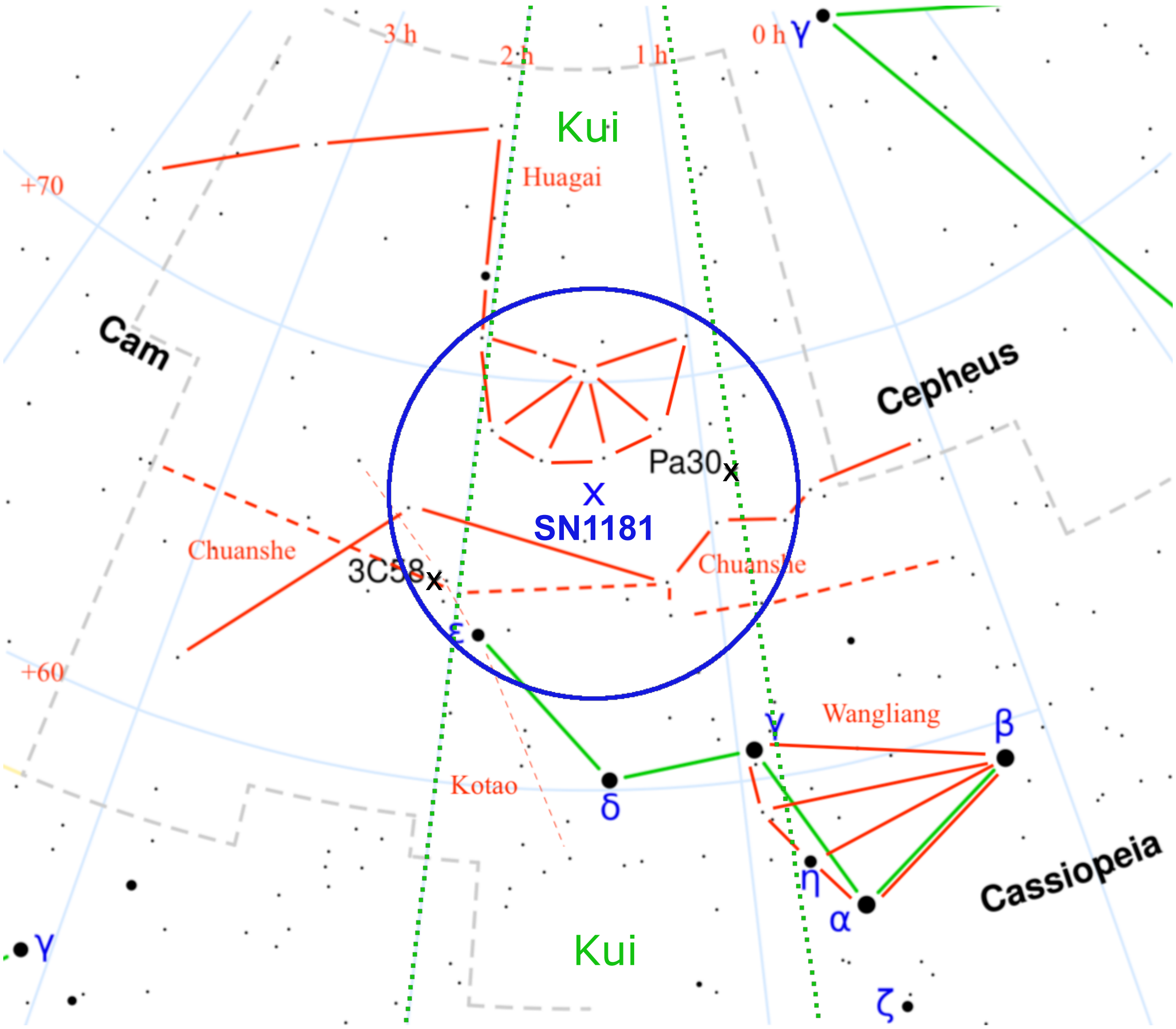


Figure 3: The region of SN 1181, as described in Hsi [1957] with the asterisms according to Hoffmann et al. [2020, their Fig A5] and Stephenson and Green [2002, their Fig 9.1. Red dashed line shows their asterism for Chuanshe] indicated. Pa 30 and 3C58 are indicated by black crosses. The green line indicates Cassiopeia. The Chinese lunar lodge Kui is between the two green dotted lines. The supernova was stated to lie between Huagai and Chuanshe, near Wangliang. The best estimated average position of SN 1181 is given by a blue cross surrounded by a blue error circle of radius 5 degrees. The background star chart was created using PP3 - Celestial Chart Generation.

Table 1: Coordinates (J2000). The original SN 1181 coordinates (e.g. 1:30, +65) have been precessed from B1950 to J2000. The uncertainty in these values remains high. The last two columns show the distance to the two candidate remnants in degrees. References to the historical positions are listed in Hoffmann et al. [2020] .

	RA	DEC	Δ(Pa 30)	Δ(3C58)
SN 1181 coordinates				
Stephenson	01:33:30	+65:15:23	4.6	3.4
Hsi	01:43:53	+70:15:05	5.3	5.8
Psovskii	01:03:12	+65:16:03	2.4	6.6
Xi	01:33:30	+65:15:23	4.6	3.4
Hoffmann	01:31:14	+70:15:53	4.4	6.3
average	01:29:04	+67:15:33	3.5	4.4
Candidate remnant coordinates				
Pa 30	00:53:11.2	+67:30:02.4		
3C58	02:05:37	+64:49:42		

2 Methods

2.1 Coordinates

The likely position of SN 1181 based on the historical descriptions is reported by Hoffmann et al. [2020] as RA: 01:31:14 DEC: +70:15:50 (J2000) with an uncertainty of ∼4 degrees (their Table 5). They also report previous determinations by four authors. We averaged all five positions, converted to J2000 coordinates. This gives RA: 01:29:04 DEC: +67:15:33. The uncertainty on the position is taken as 5 degrees.

The proposed coordinates of SN 1181 (accurate to 5 degrees) and the two candidate remnants are listed in Table 1. Based on the offsets from the proposed coordinates, both candidates are within the positional uncertainty, and on this criterion alone each appears viable.

Following Hsi [1957] and Hoffmann et al. [2020], we have compared the locations of both candidates to the original Chinese and Japanese reports described by Stephenson and Green [2002]. Two texts from China place the guest star 'in Kui lunar lodge, trespassing against Chuanshe and guarding the 5th star of Chuanshe' (South China) and 'in Huagai' (North China). A record from Japan describes it 'close to Wangliang and guarding Chuanshe'. The Kui lunar lodge and the three asterisms are depicted in Fig. 3, which is based on Fig. A5 of Hoffmann et al. [2020, we note that the declination scale in their Fig. A5 is incorrect]. Wangliang contains the brightest stars in the area being part of the modern constellation Cassiopeia. The seven stars of Huagai, although much fainter, form a well-defined cluster shaped like a parasol and are also fairly easily identified. The exact position of Chuanshe is less certain. This asterism consists of nine dim stars barely visible to the unaided eye. Two possible positions (Hoffmann et al., their Fig. A5, and Stephenson and Green, their Fig. 9.1) are shown in Fig. 3. Taken together, the supernova can be expected to have occurred in between Huagai and Chuanshe. Our averaged best estimate of its position is given by a blue cross centred on a blue error circle of radius 5 degrees. It is notable that none of the records mention the asterism Kotao (thin dashed line in Fig. 3), although it crosses Chuanshe at the location of 3C58. One would also expect that the location of 3C58 would have been better described as being close to ε Cas, a bright 3rd magnitude star. In contrast, the location of Pa 30, also denoted by a labelled black cross, fits the description well and is in better agreement with its association with Huagai. However, the descriptions are not accurate enough to decide between the two candidates on positional information alone though Pa 30 is clearly favoured.

2.2 Observations

We obtained optical spectroscopy of both the star and the nebula on 2016 July 8 using long slit observations with the OSIRIS instrument of the 10-m GranTeCan (GTC) telescope Cepa [2010] using the grism R1000B. The 7.4′ slit with a width of 0.8″ was placed at a position angle 30° East-of-North, slightly off-centre from the central star to reduce contamination from a bright field star. Total exposure time was 2 × 20 min. A factor 2 × 2 binning was used which provides a spatial scale of 0.254″/pixel (with a seeing of 1.35″) and a spectral resolution of about 2Å (R=1,000). The wavelength coverage was 3700–7000Å. We used the standard GTCMOS pipeline for the data reduction.

Earlier, the DSH team used the SparsePak integral field unit (IFU) of the Bench mounted spectrograph on the 3.5-m WIYN telescope at KPNO on 2014 October 15 to observe Pa 30 as a planetary nebula candidate. They did not see the expected emission lines and did not extract the central star's spectrum. The exposure time was 2 × 20min. The IFU mode offers 82 fibers of 4.7″ diameter, in a 72″×71″ grid [Bershady et al., 2004]. The wavelength coverage with

grating 600V (10.1 degree Littrow blaze angle) was 4280–7095Å giving a spectral resolution of 3.35Å. We re-reduced this archived data using the pipeline of Ritter and Washuettl [2004] and standard IRAF packages extracting both the star and nebula. Since the dedicated sky fibers were also placed on regions with potential nebular emission, we subtracted the sky using standard principal component analysis.

2.3 Interstellar extinction

The neutral hydrogen column density estimates [HI4PI Collaboration et al., 2016] yield an extinction of $A_V = 2.24 \pm 0.1$ mag. The higher resolution 3-D IPHAS extinction map [Sale et al., 2014] indicates a higher extinction of $A_0 = 2.52 \pm 0.40$ mag (monochromatic).

We investigated 3-D extinction maps based on the *Gaia*-2MASS [Lallement et al., 2019] and *Gaia*-PanSTARRS-2MASS [Green et al., 2019] databases. In the first case (Lallement et al.), we find a colour excess $E(B-V) = 0.87$ and therefore $A_V = 2.7$ mag. In the latter case (Green et al.), $E(g-r) = 0.70$ was found at 2.3 kpc. $E(B-V)/E(g-r) = 0.884$ to 0.996, therefore A_V ranges between 1.92 and 2.17 mag.

We also selected stars within 10 arcminutes of Pa 30 in the *Gaia* EDR3 catalogue with parallax uncertainty $\sigma_\pi/\pi < 0.5$ with a non-zero A_G from *Gaia* DR2. The median A_G is about 2.25 mag. Using Table 13 of Jordi et al. [2010], we extrapolate A_G/A_V ratios between 0.88 and 1.02 for stars hotter than 50kK, giving an interstellar extinction of $A_V = 2.4 \pm 0.2$ which we have adopted for dereddening.

3 Conclusions

The previous association of 3C58 with SN 1181 was based in part on the lack of another viable candidate, but it has a difficulty with the discrepant ages from the observed expansion velocity, proper motion of the knots, neutron star cooling models, and pulsar spin down rate [Bietenholz, 2006, Fesen et al., 2008]. Kothes [2013] proposed a much smaller distance to 3C58 than previously found (2 kpc versus 10 kpc), which reduces the age discrepancy from the expansion velocity, but this would then imply an event with a peak apparent magnitude of $m = -5$. Such a bright event disagrees with the reported comparison with Saturn, and leaves the question open why it wasn't seen in more countries. Pa 30 now provides an excellent, viable candidate for the SN 1181 eruption that fits the location, the age, the brightness and even the visible duration given its likely Type Iax nature.

We therefore conclude that Pa 30 is the remnant of the SN 1181 supernova. It was until now the only remaining historical supernovae of the last millennium without a certain counterpart. It is also the first observed supernova Type Iax event in the Galaxy and so the only one where detailed studies of the remnant star and nebula are possible, and for which the double-degenerate merger scenario has strong observational support [Gvaramadze et al., 2019, Oskinova et al., 2020]. Given the extreme nature of Parker's star itself [Gvaramadze et al., 2019, Oskinova et al., 2020] and our linking it to the 1181 AD supernova, this source is of considerable scientific and historical interest. Parker's star is the only Oxygen Wolf Rayet star known that is neither the result of a massive Pop I progenitor nor the central star of a planetary nebula, but is the result of an ONe-CO WD merger that accompanied a Type Iax supernova explosion that now has an historical basis.

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Facilities: WISE, GALEX(near UV), XMM(Newton), GTC:10.0m,OSIRIS KPNO:WIYN3.5m,SparsePak, KPNO:2.1m

Software: astropy [Astropy Collaboration et al., 2013, 2018], PP3 - Celestial Chart Generation created by Torsten Bronger, Inkscape that is Free and Open Source Software licensed under the GPL

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